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# A New Optimisation Framework for Investigating Wind Turbine Blade Designs

T. Macquart[1], V. Maes [2], D. Langston [3], A. Pirrera[4], P.M. Weaver[5]

[1] Post-doctoral Researcher, ACCIS, University of Bristol, England, terence.macquart@bristol.ac.uk
[2] Ph.D Student, ACCIS, University of Bristol, England
[3] Post-doctoral Researcher, ACCIS, University of Bristol, England
[4] Lecturer, ACCIS, University of Bristol, England
[5] Professor, ACCIS, University of Bristol, England

## 1. Abstract

We propose a new optimisation framework developed for the investigation of innovative wind turbine blade designs. The design of wind turbines has progressively evolved over recent decades as part of an ongoing effort to provide economically competitive solutions for wind energy production. In particular, rotors have increased in size so as to capture more wind energy while limiting installation costs. At the same time blade designers have had to continually improve the structural efficiency of blades in order to accommodate higher extreme and fatigue loads resulting from growing rotor diameters. Modern wind turbine designs are the result of these incremental improvements, limiting financial risks but also confining the design space and effectively reducing opportunities for more radical innovation. In this paper, we enable the wider exploration of the wind turbine blade design space by means of a new optimisation framework. For that purpose we develop and combine state-of-the-art tools for the aero-servo-elastic analysis and optimisation of wind turbines aiming to explore the uncharted design space resulting from decades of incremental changes. Our framework relies on the use of B-spline surfaces and lamination parameters to provide a compact and continuous means of describing blade structures, also enabling the use of gradient-based optimisers. This structural parameterisation is further combined with beam and shell finite element models to provide further confidence in preliminary structural designs. The proposed framework is presented and verified herein. Validation results show good agreement with the modern large scale DTU 10 MW blade design. Additionally, the coupled bend-twist behaviour of the beam model is found to agree well with higher fidelity finite element model predictions.

**2. Keywords:** Bend-Twist Coupling, Optimisation, Wind Turbine, Composite Material, Lamination Parameters

## 3. Introduction

The technological progress in wind turbine designs, driven by environmental and economical concerns, have resulted in a steady decrease of the cost of wind energy in recent decades. The cumulation of these efforts have made onshore wind energy an economically viable alternative to natural resources such as gas and coal [1]. The cost of offshore wind energy, by contrast, remains significantly higher than that of onshore and further improvements upon current wind turbine technology are needed before large offshore wind turbines become economically viable without governmental support.

The electrical power generated by a wind turbine is proportional to the area covered by its rotor. Increasing the size of wind turbine rotors in order to harness more energy has, therefore, been the primary approach employed to reduce the cost of wind energy [2]. The general trend being to build single machines with high power output instead of building many smaller turbines. The issue with this approach is that the rates at which design driving loads such as fatigue and extreme loads increase with rotor sizes is generally greater than the rate of increased energy capture. Up-scaling older wind turbine technology is, as a result, not an economically viable solution and designers must continually improve their designs so as to balance this power to load trade-off as wind turbines scale increases [3].

Materials with high stiffness to weight ratios have played a vital role in the design of stiff yet light blades, moving from wood and metals to composites such as fibreglass. Fibreglass composites have made possible the design of large wind turbines by providing blades with additional bending stiffness while mitigating the increase in blade mass [4]. However, even the structural advantages of fibreglass will eventually become insufficient as wind turbine sizes continue to increase [5]. Although replacing fibreglass by higher stiffness to weight ratio composites such as carbon fibre could be envisaged, the economic competitiveness of carbon fibre prices for future wind energy applications remains uncertain. Instead, new wind turbine designs and more radical developments may be needed for still larger rotors.

The design of wind turbines has mostly been incremental and there has been limited change to the blades internal spar box over the last decades. Older tools developed for blade analyses are, as a result, heavily reliant on conventional designs and original assumptions made for more rigid blades [6]. Only recently significant efforts have been made to account for all blade structural couplings [7, 8]. The newly opened design space for exotically coupled blades remains, however, vastly unexplored.

Herein, we set forth a plan to explore this design space and investigate some innovative solutions for large offshore wind turbine blade designs. For that purpose, a new framework for the analysis, design and optimisation of wind turbines is currently being developed. This paper serves as an introduction to this framework's current and future capabilities. One of these innovative solutions, the concept of large scale bend-twist coupled blades, is used as a demonstrative case study in this paper. The primary motivations behind the development of this new framework are listed below.

- Accurately predicting the dynamic behaviour of blades using beam models can be challenging. The increased variability of structural properties along the blades can exacerbate numerical errors resulting from the modelling assumptions originally derived for prismatic structures. That is particularly true when secondary structural blade couplings are to be investigated (e.g. bend-twist). Our motivation is therefore to provide a computationally cheap yet accurate means of predicting the blades coupled dynamics, and cross-sectional strains and stresses. We have, for that purpose, started the development of a high-order beam model [9] which will continue to evolve so as to include refined coupled beam and cross-sectional models such as the Unified Formulation [10]. Additionally, we have also developed a code for the automated generation and analysis of blade shell models in order to provide additional confidence in the preliminary blade designs based on beam models.

- The NREL provides a wide range of free tools for the analysis of modern wind turbines. However, employing these tools within an optimisation framework is not trivial [11]. That is in part because of difficulties coupling each code but also due to the discrete nature of material variables such as ply angles and thicknesses required to describe the blades structure in detail which preclude the use of fast and effective gradient based optimisers. The search for innovative wind turbine blade designs through optimisation, therefore, requires significant development efforts and computational power. Our second motivation is to propose a compact and continuous parameterisation of the blade structures in order to enable gradient-based optimisations. This parameterisation based on lamination parameters and B-spline surfaces replaces the heavy and cumbersome conventional approach relying on laminate stacking sequences.

- Bend-twist coupled blades are designed to passively react to local winds in order to mitigate loads [12]. More precisely, the concept investigated herein is designed to twist-to-feather reducing the angle of attack as a result of flapwise bending loads, effectively reducing the aerodynamic forces experienced by the deflected blades. In turn, this reduction in load shifts the power to load trade-off in favour of power. As a result, larger wind turbines generating more power but subject to equivalent loads could be designed. Although there has been a few previous studies on bend-twist coupled blades [13], the actual benefits of this technology remain unclear due to a combination of modelling and manufacturing difficulties, as well as limited experimental data. In particular, predicting the bend-twist behaviour of blades using beam and even shell models can be difficult. For beams, it requires an accurate estimate of the cross-sectional stiffness and mass matrices as well as 3D beam elements that can account for bend-twist couplings. Even with all these, convergence may still require numerous elements in order to accurately describe the variation of twist and shear strains along the blade length. High accuracy whilst predicting bend-twist is, however, crucial since aerodynamic blade loads are extremely sensitive to twist. Our last motivation is, therefore, to employ this new framework in order to investigate the capabilities of large scale bend-twist coupled blades.

The aim of the developed framework is to provide a single design and optimisation tool which describes in a compact manner the variations of structural properties along the blade span while also computing cross-sectional and beam properties, and performing aero-elastic analyses.

## 4. Wind Turbine Optimisation Framework

A brief overview of the proposed optimisation framework is presented in this section. It implements a simple architecture in which the multidisciplinary analysis model is directly coupled to an optimiser. The extended design structure matrix standard developed by Lambe and Martins [14] is used to represent the framework architecture in Figure 1. The design variables shown on the right hand side of the optimiser are fed into the different analysers represented by green boxes (e.g. structural, aerodynamic). The analysers can in turn feed their outputs to other analyser and/or to the optimiser as constraints or objectives.

As shown in Figure 1, running an aeroelastic wind turbine analysis requires various analysers. That includes a three-dimensional turbulent wind field generator such as TurbSim [15], an aerofoil aerodynamic module or database to provide the lift, drag and moment coefficients of aerofoil profiles for specific wind conditions. A cross-sectional modeller is also necessary in order to compute the blade cross-sectional stiffness and mass matrices needed for constructing and solving the finite element beam model. The beam model is then coupled to an aerodynamic and control model to perform aero-servo-elastic simulations which output time dependent power, loads and deflections. These can finally be post-processed in order to evaluate fatigue, annual energy production (A.E.P), and the levelised cost of energy (L.C.O.E) of the proposed design.

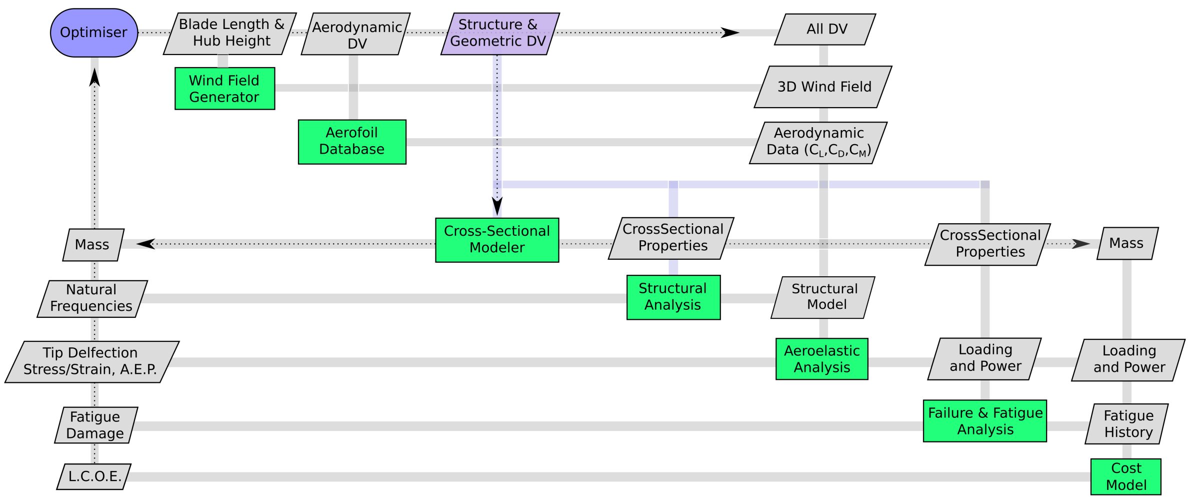



Figure 1: Block diagram of the proposed multi-disciplinary optimisation framework.
'DV' refers to design variables.

The solution to this optimisation problem depends on the specified design variables, objectives, and constraints. The general form of the optimisation problem solved by our framework is given as:

$$\min_{\mathbf{x}} f_0(\mathbf{x}), \tag{1}$$

$$\text{subject to } f_i(\mathbf{x}) \leq 0 \quad , \ i = 1,\ldots,m \quad , \tag{2}$$

$$\mathbf{x}_{lower} \leq \mathbf{x} \leq \mathbf{x}_{upper}, \tag{3}$$

where $\mathbf{x}$ is the vector of design variables, $f_0$ is the objective function to minimise and $f_i$ are inequality constraints. In addition, the design variables are prescribed within upper and lower boundaries, $\mathbf{x}_{upper}$ and $\mathbf{x}_{lower}$ respectively. Note that the optimisation framework is not yet complete and that full aero-servo-elastic optimisation are not yet possible. Instead, the authors proposed blade structural parameterisation is detailed and validated in the rest of this paper.

## 5. Blade Structural Parametrisation

Blade modelling is key in order to accurately estimate the energy capture and loads experienced by wind turbines. The conventional internal geometry of blades illustrated in Figure 2 includes:

- Spar caps, mostly made of unidirectional fibres, which are the main flapwise bending carrying load components.
- Two webs linking the spar caps providing shear and torsional stiffness, as well as preventing nonlinear cross-sectional distortions (e.g. Brazier type effects) . In large blades, webs are usually sandwich laminates made of a balsa or foam core with $\pm 45^\circ$ fibres on the outer layers in order to provide additional shear stiffness. A third web is sometimes also added towards the aerofoil trailing edge in order to provide additional resistance to buckling.
- Leading and trailing edge panels provide small amounts of bending stiffness and help maintain a somewhat rigid aerofoil profile for aerodynamic performance.
- Local reinforcements at the leading edge nose and at the trailing edge tail are also used in order to locally increase edgewise stiffness and buckling resistance. The trailing edge design is generally driven by local failure such as debonding.

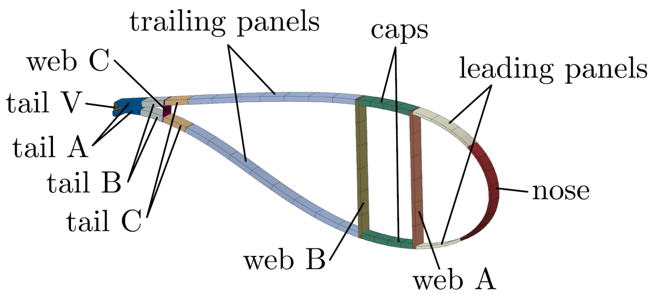



Figure 2: Conventional internal blade structure, original figure from [16]

The conventional design of the blades' internal geometry is often restricted by the proportion and directions of fibre angles allowed which are usually pre-fixed as parts of material definitions. A typical example is given in the DTU 10 MW blade design [16] in which the laminates are referred to as UNIAX, BIAX and TRIAX. UNIAX, mostly used in the caps, denotes a $0^\circ$ dominated laminate including a small percentage of $90^\circ$ degree plies. BIAX refers to $\pm 45^\circ$ laminates used in the webs. TRIAX describes a mix of $0^\circ$ and $\pm 45^\circ$ plies used in most part of the blades but primarily in the root section. While such categorisation of laminates greatly simplifies the description of blade structures, it potentially rules out a lot of alternative design possibilities. That said, the conventional choices of predefined layups are quite justified as the fibres are mostly aligned with the dominant loads in each components whilst also being simple to manufacture. As such, current blade designs provide a good trade-off between structural efficiency and simplicity. By contrast, it is not clear whether or not more exotic layers could provide better overall performance by taking advantage of aeroelastic effects such as bend-twist couplings. Allowing each laminate ply angle to be optimised would, however, result in a very large and non-convex design space. We propose an innovative structural parameterisation in order to address this issue.

The vast design space associated with the optimisation of composite structures has encouraged the development of new material parameterisations. Wherever a composite laminate is used its equivalent stiffness and strength properties must be evaluated before the blade structural performance can be assessed. Classical laminate theory (C.L.T.) provides a straightforward means of determining the stiffness properties of a laminate based on its stacking sequence (i.e. assembly of plies). Although describing the stiffness properties of a composite structure using stacking sequences and C.L.T. is simple, it requires a great number of variables directly proportional to the number of plies (e.g. ply orientation and thickness). Additionally, the design space obtained whilst employing stacking sequences is non-convex and often contains many local optima making the fast and thorough optimisation of large structures based on stacking sequences a nearly impossible task. Parameterising composite laminates using lamination parameters provides a solution to this problem [18]. By taking advantage of material invariant properties, a set of twelve lamination parameters and one thickness variable are fully sufficient to express the stiffness of any

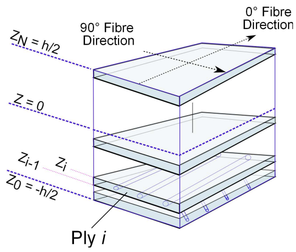



Figure 3: Stacking sequence notation

laminate. Take, for example, the in-plane stiffness matrix evaluated with C.L.T. as follows

$$[A] = \sum_{i=1}^{N} [Q']_i (Z_i - Z_{i-1}), \tag{4}$$

where the upper and lower height location of ply $i$ within the laminate are given by $Z_i$ and $Z_{i-1}$ as illustrated in Figure 3, and $[Q']_i$ is the orientated stress/strain stiffness matrix. Tsai and Hahn [17] showed that the stress/strain stiffness matrix of a randomly oriented $\theta_i$ ply can be expressed as linear combinations of material invariants $U's$ and trigonometric functions such that

$$[Q']_i = f([Q]_i, \theta_i, \mathbf{U}_i), \tag{5}$$

in which $[Q]_i$ is stress/strain stiffness matrix expressed in the ply principal axes, $\theta_i$ is the angle between the principal and reference axes, and $\mathbf{U}_i$ is a vector of material invariants. Substituting the $[Q']_i$ by their equivalent material invariants and trigonometric functions in Eq. (4) one can rewrite the in-plane stiffness matrix as

$$[A] = \sum_{i=1}^{N} \left( [T_0]_i + [T_1]_i \cos(2\theta_i) + [T_2]_i \cos(4\theta_i) + [T_3]_i \sin(2\theta_i) + [T_4]_i \sin(4\theta_i) \right) (Z_i - Z_{i-1}), \tag{6}$$

in which the material invariants $U$ are regrouped into the invariant matrices $[T_0]$, $[T_1]$, $[T_2]$, $[T_3]$ and $[T_4]$. When a laminate is made of the same plies but orientated in different directions, the material invariants are constant and the corresponding expression for the stiffness matrix can further be simplified as

$$[A] = h \left( [T_0] + [T_1] V_1^A + [T_2] V_2^A + [T_3] V_3^A + [T_4] V_4^A \right), \tag{7}$$

with $h$ being the laminate total thickness, and the in-plane lamination parameters defined as

$$\begin{array}{ll} V_1^A = \frac{1}{h} \sum_{i=1}^{N} \cos(2\theta_i)(Z_i - Z_{i-1}), & V_2^A = \frac{1}{h} \sum_{i=1}^{N} \cos(4\theta_i)(Z_i - Z_{i-1}) \\ V_3^A = \frac{1}{h} \sum_{i=1}^{N} \sin(2\theta_i)(Z_i - Z_{i-1}), & V_4^A = \frac{1}{h} \sum_{i=1}^{N} \sin(4\theta_i)(Z_i - Z_{i-1}) \end{array} . \tag{8}$$

Comparing Equations (4) and (7), it is clear that one can use the four in-plane lamination parameters as design variables and effectively replace the $N$ variables previously needed to describe the orientation of each ply within a $N$-ply laminate as C.L.T. requires in Eq. (4). A further eight lamination parameters are necessary in order to include the out-of-plane and coupled stiffness matrices. This mean employing lamination parameters reduces the number of design variables from $N$ to thirteen for each laminate, a considerable advantage for large structures made of hundreds of laminates. Even more important than the significant reduction of variables required to describe a laminate, lamination parameters are continuous variables. Employing lamination parameters, therefore, leads to a composite optimisation problem reformulated in a continuous space for which computationally fast and effective gradient based optimisers can be employed. It should, however, be noted that lamination parameters are not independent design variables and that a set of constraints is required during optimisation [19].

In view of the above mentioned advantages, the developed framework employs lamination parameters for describing the variation of properties along the blades. Lamination parameters and thickness variables are defined at control points along the wind turbine blades and used in combination with B-spline surfaces in order to describe the spanwise and chordwise variation of structural properties, as illustrated in Figure 4. B-splines are chosen, amongst others, for their convex hull property which ensures the feasibility of lamination parameters over the entire surfaces if the values at control points are feasible [19].

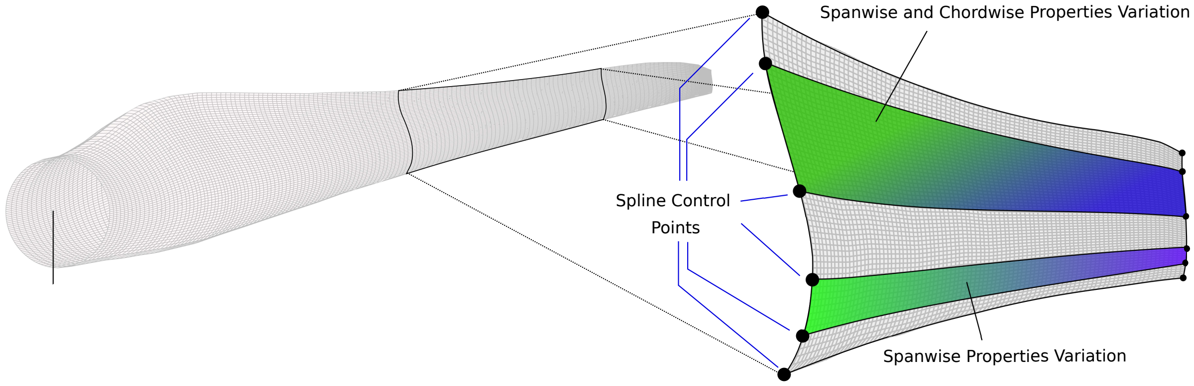



Figure 4: Spline surface and lamination parameters

Isotropic, single laminate and sandwich regions are modelled as shown in Figure 5. Note that while surfaces illustrated in this figure are only described using four control points, the number of spanwise and chordwise control points within a spline surface can be set to any integer value. Employing more points effectively refines the surface mesh and provides additional local control over the variation of structural properties. Furthermore, if all control points within the same surface are set to identical values then the region becomes equivalent to a straight fibre laminate. The variations of thickness over an isotropic part is described using a single spline surface. On the other hand, the variation of structural properties along a laminated part is represented using thirteen spline surfaces. Twelve surfaces describing the variation of lamination parameters and one surface for the laminate thickness. Finally, sandwich structures are described using a combination of core thickness and lamination parameters. Although the number of surfaces used to fully describe a blade-like structure may seem large, this number is small in comparison to the number of design variables that would be required in order to describe an entire blade layups with similar tailoring capabilities (e.g. thousand of plies). The number of lamination parameter surfaces would also decrease if only symmetric and/or balanced laminates are considered. More importantly, the design variables associated with the B-spline surfaces are continuous and can be optimised using gradient-based optimisers, effectively speeding up and possibly convexifying the optimisation process.

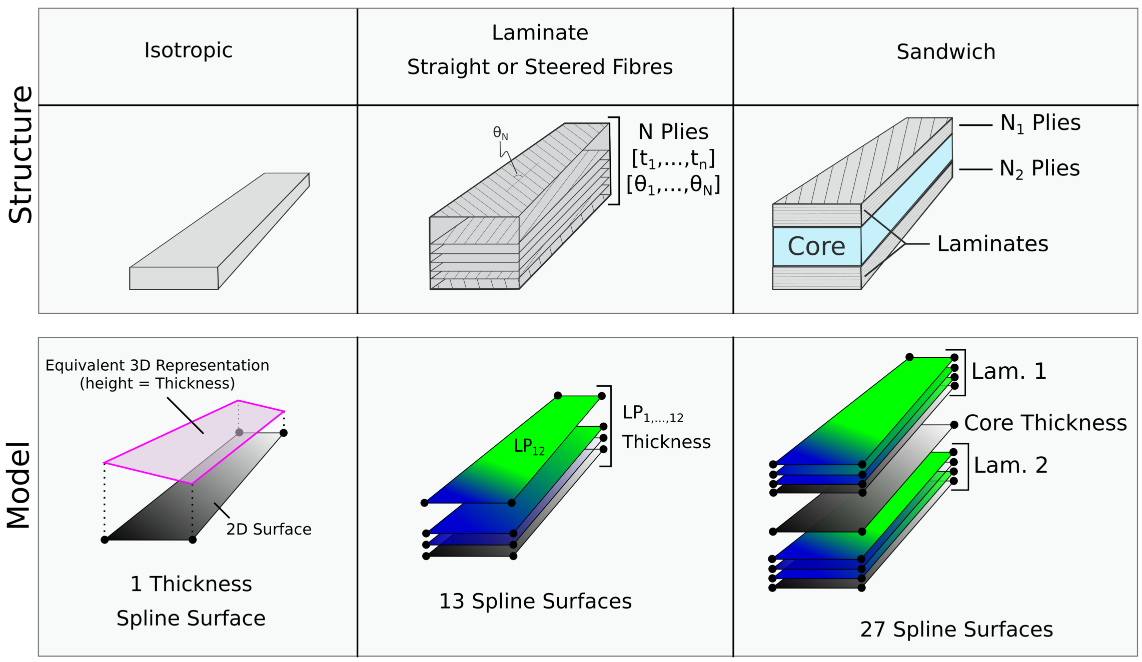



Figure 5: Structural parameterisation based on spline surfaces and lamination parameters

## 6. Structural Model of the Blade

In this section the procedure by which the distributed structural properties of the blade are used to calculate the stiffness and mass matrix of the blade beam model is presented as illustrated in Figure 6. The blade is divided into beam elements of uniform length along a beam axis (i.e. blue line), and cross-sectional properties are evaluated at multiple points along the element length. For that purpose, the blade geometry and the spline surfaces are interpolated in order to generate two-dimensional cross-sectional finite element models. Solving these models yields the variations of cross-sectional stiffness and mass matrices along the beam element length. These properties are then integrated spanwise along the beam axis in order to obtain the equivalent beam stiffness and mass matrices.

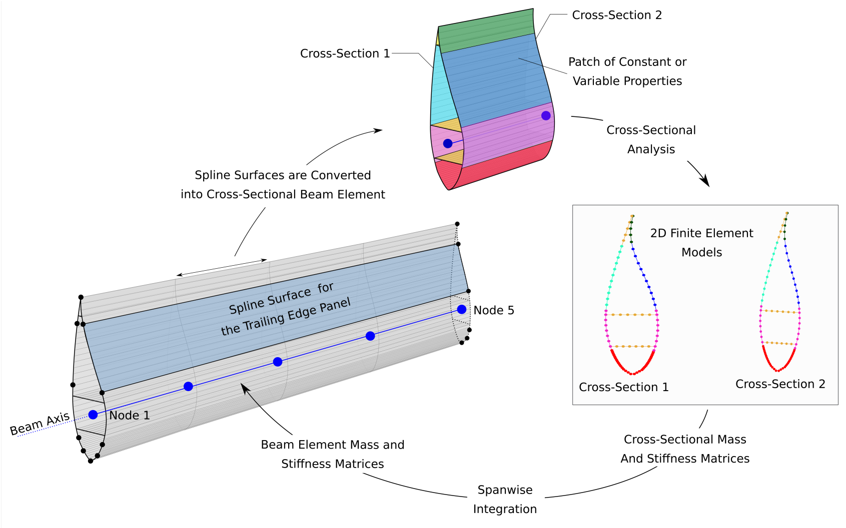



Figure 6: Structural model analysis

The structural model developed for the present framework has a couple of specific developments. A beam element can have two, three, and any higher integer number of nodes. Increasing the number of nodes within a single element increases the order of displacement shape function which in turn leads to faster convergence and smoother strain predictions between elements. Additionally, the beam elements are not assumed to be prismatic and therefore cross-sectional properties are allowed to vary along the element length. Multiple cross-sections are modelled along a single beam element in order to capture cross-sectional property variations and accurately integrate them over the element length. The result is an accurate calculation of the beam element stiffness and mass matrices, improving the beam model convergence rate. Further details regarding this model can be found in [9].

## 7. Verification of the Structural Model Parametrisation

The eigenfrequencies and mode shapes predicted by the structural beam model based on B-spline surfaces and lamination parameters are verified in this section. Accurate modal results are crucial since modal reduction is necessary in order to lower the computational effort associated with the dynamic simulation of blades over hours of simulated operating time. Although non-linear structural analysis may be required in order to achieve more accurate results for highly coupled blades, its computational burden is often considered too high for aeroelastic simulation of preliminary wind turbine designs.

### 7.1. Conventional Design

The DTU 10 MW wind turbine blade is chosen as a comparison model due to its freely available geometrical and structural data [16]. The blade is divided into circumferential regions (e.g. spar cap) as illustrated on the left hand side of Figure 7. Each region represents a sandwich laminate made up of either three or five layers spanning the entire blade length. Additionally, each layer is associated with up to thirteen spline surfaces describing the variations of properties such as thickness and stiffness in the blade spanwise direction as illustrated on the figure's right hand side. Equivalent [A], [B] and [D] stiffness matrices are then computed at each point along the blade.

The original blade data available in the literature is used to build an equivalent model based on the authors' parameterisation. We validate this model by comparing the modal analysis results of our beam model against the mixed shell/solid model provided by DTU [16]. The results of this comparison for the first four modes are presented in Figure 8. As observed in this figure, good agreement is achieved between both approaches. In particular, it should be noted that the beam model provides a good insight into the blade dynamics considering its relative simplicity compared to the original shell/solid model. Small discrepancies in eigenfrequencies and mode shapes that can be attributed to modelling approximations (i.e. glue and webs position) and assumptions linked to the beam model (i.e. rigid cross-section) are also observed as one would expect. This first verification gives the authors confidence that the proposed parameterisation can be used to predict the behaviour of conventional wind turbine blade designs with reasonable accuracy.

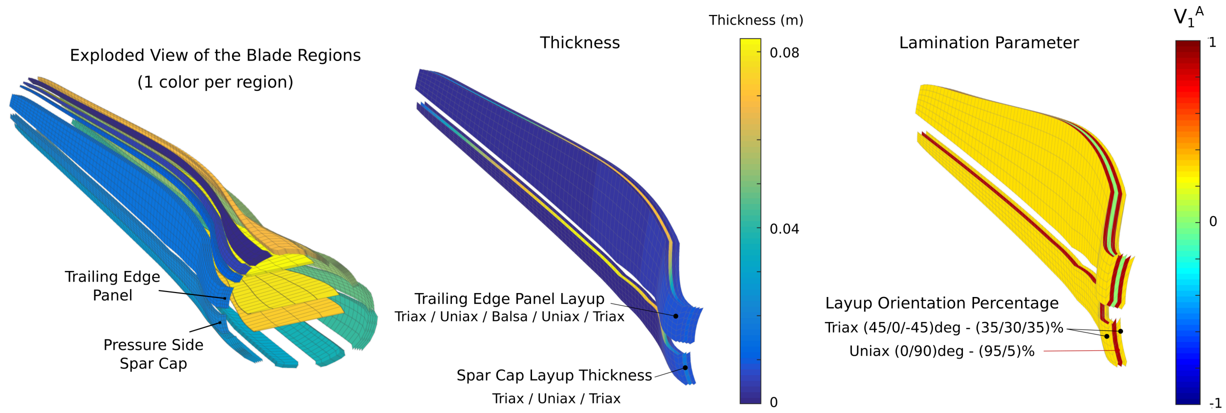



Figure 7: Exploded view of the DTU 10MW blade modelled using the present framework

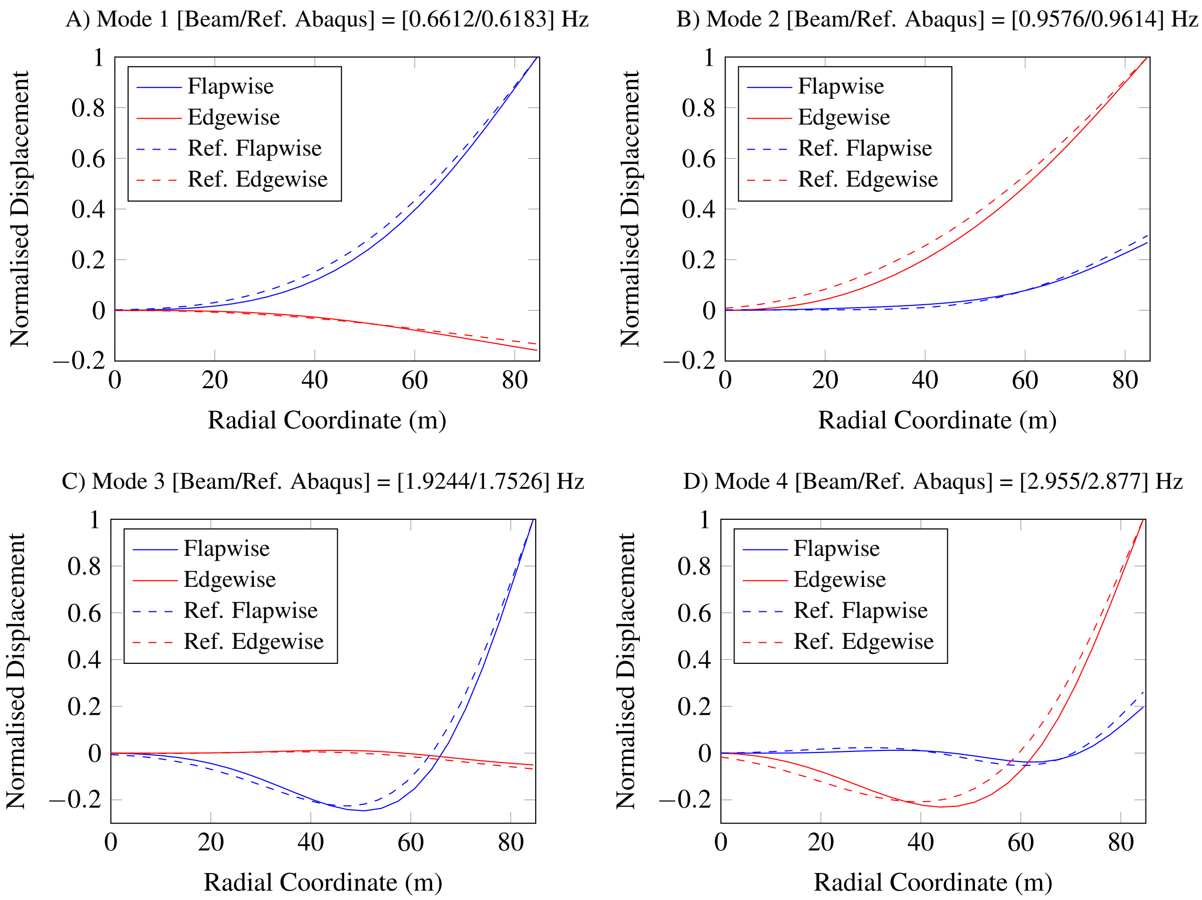
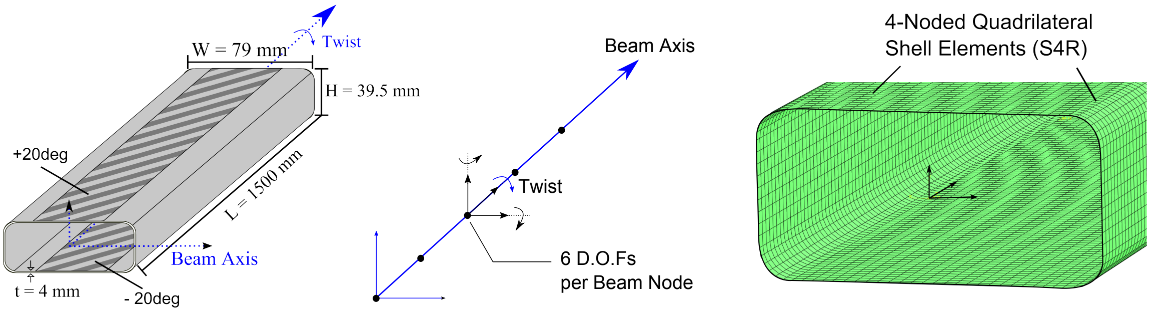



Figure 8: Modes 1, 2, 3 and 4 beam model comparisons with a mixed shell/solid Abaqus model

7.2. Material Bend-twist Coupling

In this section the beam model predictions for material bend-twist coupling induced by off-axis fibre orientation are evaluated and compared against the predictions of a shell model. The small scale internal spar box illustrated in Figure 9a is used as our first case study. The beam finite element model of the spar box is defined along a beam axis passing through the centroid of each cross-section. The beam axis is uniformly divided along the spar box length into 3-noded Timoshenko beam elements, with three translations and three rotations associated with each node as shown in Figure 9b. By contrast, the spar box shell element model is a geometrically accurate representation of the spar box as featured in Figure 9c. Reference points located at the centroid of cross-sections along the spar box length are added to the shell model. The deformations measured at these reference points, also lying on the beam axis, provide a meaningful comparison between the shell and beam models deflections. For that purpose, the nodes of shell elements along cross-sections are tied to their respective reference nodes as illustrated on the left hand side of Figure 10.

The spar box modal responses for the first flapwise bend-twist mode obtained with the beam and shell models are presented in the right hand side of Figure 10. This figure shows that the flapwise deflection predicted by both models match perfectly. On the other hand, the twist response predicted by the shell model is shown to vary between lower and upper bound values. That is because the shell model's reference points lying along the beam axis are coupled to the cross-sections which numerically stiffens the spar box torsional response. Varying the number of cross-sectional couplings and their types (e.g. kinematic, structural couplings) used along the spar box effectively alters the spar box torsional rigidity which in turn result in a range of possible twist values as shown in Figure 10. As observed in this figure, the beam model twist prediction falls within the predicted shell range. Future work is, however, required in order to better understand the effect of cross-sectional stiffening and reduce the shell model range of predictions. Although a typical bend-twist coupling benchmark case study, this small spar box example is not representative of large scale wind turbine blades. In particular, the twist induced due to bending in long blades is generally much smaller and error of prediction observed for the spar box may be greatly reduced.




(a) Spar box schematic

(b) Beam model

(c) Abaqus Shell model close-up

Figure 9: Spar box material bend-twist coupling case study

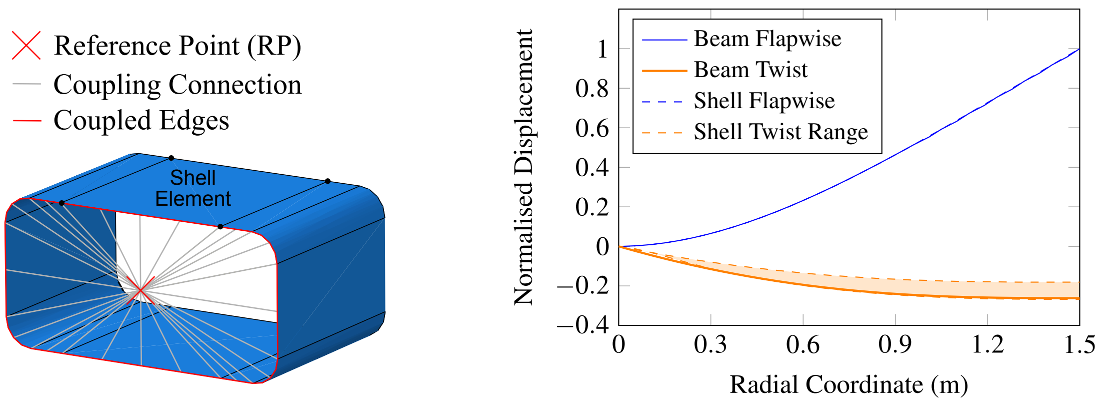



Figure 10: Spar box shell coupling (right) and first modal response (left)

The material bend-twist coupling verification is extended to the DTU 10MW blade model in order to assess the bend-twist accuracy predictions for more conventional wind turbine blade design. In this case, the original blade is modified such that the spar cap fibre directions are set to $+30$ and $-30$ for the upper and lower skin respectively. The first bend-twist coupled mode predicted by both the beam and shell models is shown in Figure 11. As for the spar box example we observe a good match between bending deflections. As expected the induced twist due to flapwise bending is also much smaller, however, we also find that the shell model twist prediction varies over a wide range of values. Although the numerical uncertainty associated with twist prediction is found to be relatively small with respect to the overall blade deflection, it is non-negligible whilst designing bend-twist coupled blades since the aerodynamic performance is very sensitive to twist.

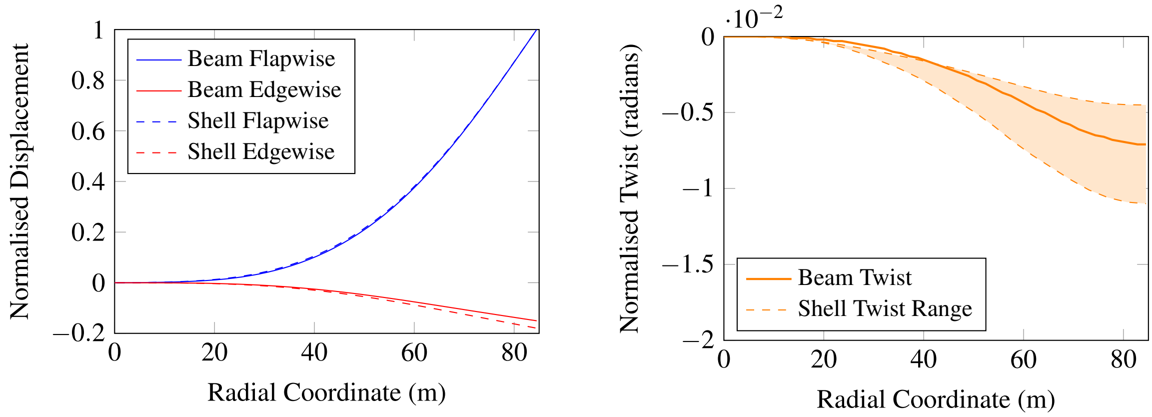


Figure 11: First flapwise-bending coupled mode for the DTU 10MW material bend-twist design

7.3. Geometric Bend-twist Coupling

In this section the beam model predictions for geometrical bend-twist coupling induced by blade sweep are compared to the shell model results. In comparison with the previous section in which we evaluate the bend-twist coupling due to off-axis fibre orientation, the twist in this model is purely linked to the geometric shape of the blade. For that purpose, the DTU 10MW blade internal structure is kept identical to the original definition [16] whilst a quadratic sweep distribution is added so as to induce a twist as the blade outer region bends in the flapwise direction as shown in Figure 12. As previously, the first bend-twist coupled modal response is shown in Figure 13. We find that the bending deflections between both model are in agreement. Additionally, we see that even this small sweep (i.e. about 15% of the blade span) induces overall more bend-twist coupling than employing off-axis fibre orientation for the entire blade spar caps. However, as for the material bend-twist coupling, we find that the twist induced by pure geometric coupling predicted by the shell model can vary significantly as a function of the cross-sectional coupling method employed to estimate it. More precisely, coupling all cross-sections to their respective beam axis reference points tends to stiffen the blade. Furthermore, the kinematic coupling method which eliminates the cross-sectional D.O.Fs and constrained the cross-sectional nodes to move with the rigid body motion of the reference beam axis node is found to have the more stiffening effect.

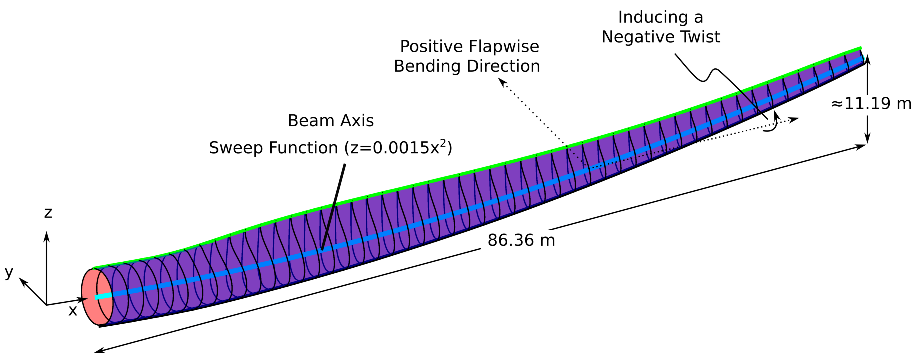
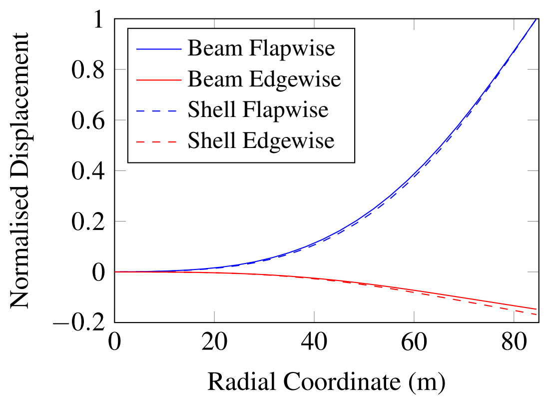


Figure 12: Geometrical bend-twist coupling case study, swept DTU blade



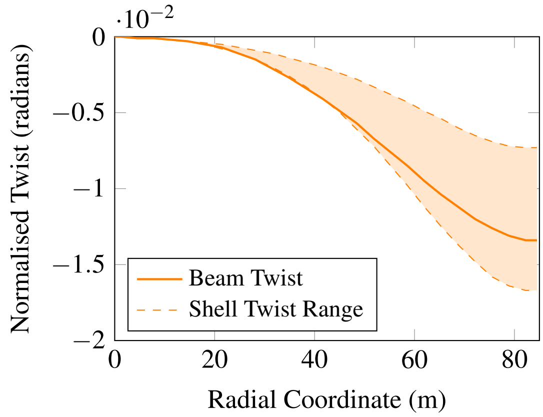




Figure 13: First flapwise-bending coupled mode for the DTU 10MW geometric bend-twist design

**8. Concluding Remarks**

The design of wind turbines has followed an incremental procedure over the last decades, effectively limiting the potential opportunities for more innovative designs to emerge. Additionally, most tools currently available for wind turbine modelling are not well-suited for effective gradient-based optimisation. A considerable part of the wind turbine blade design space remains, as a result, vastly unexplored. In this paper we proposed a new framework for investigating non-conventional wind turbine blade design concepts, employing optimisation as a means to explore this uncharted design space. For that purpose, the authors have developed and presented a compact and continuous parameterisation of the blade structure in order to replace the heavy and cumbersome use of classical laminate theory and stacking sequence in optimisation. The proposed parameterisation, based on B-spline surfaces and lamination parameters, was also shown to be able to successfully reproduce the design of a large scale 10 MW wind turbine blade. Furthermore, our preliminary investigation of the bend-twist coupling response of blade calls for caution. Although the beam model twist responses converges relatively quickly, the bend-twist coupling predicted by the refined shell models were found to vary over a wide range of values, making it difficult to confidently assess the bend-twist coupling amplitude. The different methods, such as kinematic or structural coupling, employed to estimate the shell models twist responses were found to significantly affect the outcome. These numerical couplings effectively stiffen the blades to different degree affecting the predicted resonance frequencies. Although these couplings have little effect on the prediction of the dominant bending vibrations, they significantly alter the degree of twist coupling associated with these bending modes. Considering the aerodynamic blade sensitivity to twist, these numerical uncertainties must be treated with caution whilst designing bend-twist coupled blades. Our future work encompasses further effort into bend-twist model prediction as well as the gathering and generation of experimental data on bend-twist coupling, that is critically missing in the current literature. Additionally, some effort will be investigated into the development of a more robust method for meaningfully comparing beam and shell finite element results. Finally, the authors plan on verifying and validating their aero-servo-elastic framework before employing it to explore new blade designs.

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**10. References**


**[1]** Salvatore, J., 2013. World Energy Perspective: Cost of Energy Technologies. *World Energy Council*, London, UK.

**[2]** Islam, M.R., Mekhilef, S. and Saidur, R., 2013. Progress and recent trends of wind energy technology. *Renewable and Sustainable Energy Reviews*, 21, pp.456-468.

**[3]** Sieros, G., Chaviaropoulos, P., Srensen, J.D., Bulder, B.H. and Jamieson, P., 2012. Upscaling wind turbines: theoretical and practical aspects and their impact on the cost of energy. *Wind energy*, 15(1), pp.3-17.

**[4]** Veers, P.S., Ashwill, T.D., Sutherland, H.J., Laird, D.L., Lobitz, D.W., Griffin, D.A., Mandell, J.F., Musial, W.D., Jackson, K., Zuteck, M. and Miravete, A., 2003. Trends in the design, manufacture and evaluation of wind turbine blades. *Wind Energy*, 6(3), pp.245-259.

**[5]** Buckney, N., Pirrera, A., Weaver, P. and Griffith, D.T., 2014. Structural Efficiency Analysis of the Sandia 100 m Wind Turbine Blade. *In 32nd ASME Wind Energy Symposium (p. 0360).*

**[6]** NWTC Information Portal (FAST v7). https://nwtc.nrel.gov/FAST7. Last modified 23-September-2015 ; Accessed 26-March-2017

**[7]** Blasques, J.P., Bitsche, R.D., Fedorov, V. and Lazarov, B.S., 2015. Accuracy of an efficient framework for structural analysis of wind turbine blades. *Wind Energy*.

**[8]** Guntur, S., Jonkman, J.M., Jonkman, B., Wang, Q., Sprague, M.A., Hind, M., Sievers, R. and Schreck, S.J., 2016. FAST v8 Verification and Validation for a MW-scale Wind Turbine with Aeroelastically Tailored Blades. *In 34th Wind Energy Symposium* (p. 1008).

**[9]** Macquart, T., Pirrera, A. and Weaver, P., 2017. A Finite Beam Element Framework for Variable Stiffness Structures. *In 25th AIAA/AHS Adaptive Structures Conference* (p. 1873).

**[10]** Pagani, A. and Carrera, E., 2017. Large-deflection and post-buckling analyses of laminated composite beams by Carrera Unified Formulation. *Composite Structures.*

**[11]** Ashuri, T., Zaaijer, M.B., Martins, J.R., Van Bussel, G.J. and Van Kuik, G.A., 2014. Multidisciplinary design optimization of offshore wind turbines for minimum levelized cost of energy.*Renewable Energy*, 68, pp.893-905.

**[12]** Runkel, F., Reber, A., Molinari, G., Arrieta, A.F. and Ermanni, P., 2016. Passive twisting of composite beam structures by elastic instabilities. *Composite Structures*, 147, pp.274-285.

**[13]** Capuzzi, M., Pirrera, A. and Weaver, P.M., 2015. Structural design of a novel aeroelastically tailored wind turbine blade. *Thin-Walled Structures*, 95, pp.7-15.

**[14]** Lambe, A.B. and Martins, J.R., 2012. Extensions to the design structure matrix for the description of multidisciplinary design, analysis, and optimization processes. *Structural and Multidisciplinary Optimization*, 46(2), pp.273-284.

**[15]** Jonkman, B.J., 2009. TurbSim user's guide: Version 1.50.

**[16]** Bak, C., Zahle, F., Bitsche, R., Kim, T., Yde, A., Henriksen, L.C., Hansen, M.H., Blasques, J.P.A.A., Gaunaa, M. and Natarajan, A., 2013. The DTU 10-MW reference wind turbine. *Danish wind power research.*

**[17]** Hahn, H.T. and Tsai, S.W., 1980. Introduction to composite materials. *CRC Press*.

**[18]** Macquart, T., Werter, N. and De Breuker, R., 2016. Aeroelastic Design of Blended Composite Structures Using Lamination Parameters. *Journal of Aircraft*, pp.1-11

**[19]** Wu, Z., Raju, G., White, S. and Weaver, P., 2014. Optimal Design of Postbuckling Behaviour of Laminated Composite Plates using Lamination Parameters. *In 55th AIAA/ASMe/ASCE/AHS/SC Structures, Structural Dynamics, and Materials Conference* (p. 1376).